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# Pulsed Laser-Induced Reactive Processing of CVD-Diamond Substrates under Liquid Ambient: A Process for 3-D Multi-Chip Modules

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# 1. Summary

Drilling of diamond substrates, using pulsed Nd-YAG laser, in water environment showed time efficient processing (about 28 times faster than in an air environment). In addition, better hole uniformity was observed in water environment than in an air environment. In water, the *hot* laser plasma on the substrate surface generates a reactive oxygen and/or hydrogen environment that increases drilling speed and makes it more uniform size hole. Diamond substrate drilling process with a pulsed Nd-YAG laser in an air environment generates significant audio noise and shock waves that can generate cracks at the processing boundary and break the thin diamond substrate during processing. The liquid environment reduces audio noise and dampens the shock wave. Therefore, laser drilling in a liquid medium is a useful method for drilling brittle materials such as diamond. After the shaping of the diamond substrate in the liquid medium, gold was successfully deposited on diamond substrates using an argon ion laser by changing the liquid medium from deionized water to the gold precursor solution.

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## 4. TECHNICAL BODY OF THE PROJECT REPORT

### 4.A Introduction and Statement of the Problem:

Diamond is an excellent thermal spreader material that can be used in high-density electronic devices, high power laser diodes, and other advanced applications [1]. For these applications, drilling and patterning of diamond substrates are essential steps in diamond heat spreader substrate fabrication process. Diamond is one of the hardest known materials; it is not easily cut or shaped. Reactive Ion Etching (RIE) can be used for dry etching of single crystal diamond or polycrystalline diamond substrates [2-3]; however, RIE patterning is time intensive and requires several intermediate steps such as a lithography. Also, for materials like diamond, RIE could lead to anisotropic etching.

A laser is a monochromatic source of light that has a very high intensity. This makes it a useful tool for materials processing, such as cutting, drilling, welding, and material deposition [4]. Laser processing is chemically clean and a fast method for shaping CVD diamond films [5-7]. Significant research has been done in the shaping of CVD diamond films using various lasers. Excimer lasers that produce nanosecond pulsed ultraviolet light have been used for diamond ablation [5-6]. Nd-YAG lasers [8], multiple laser processing with excimer and Nd-YAG lasers [9], and Ar-ion lasers [7] have also been used. Ral'chenko [7] used an Ar-ion laser to make patterns on CVD diamond films in oxygen and air environments, and achieved a 50 μm/sec etching rate. This experiment required a vacuum chamber to allow use of various gas environments; therefore, making the process complex. Furthermore, the gases used were very corrosive/explosive, making the process potentially very dangerous [7].

Nd-YAG lasers are high energy density pulsed lasers. Presence of a liquid medium, at the laser/solid interface during interaction can generate a "reactive" medium. The liquid environment may have radicals either for etching or deposition. Thus, the selection of "right" environment can significantly enhance the etching or deposition rate, as compared to gaseous ambient, due to higher density of radicals in liquid medium.

When the substrate is illuminated with a Nd-YAG laser beam, a loud noise and a strong shock wave are generated. CVD diamond substrates are brittle; thus, they are easily shattered by the laser beam induced shock waves [10]. This shock wave could be significantly dampened by a

liquid medium. Further, reaction chamber for "reactive" laser processing is simple and manufacturing transparent.

Lasers can also be used for the deposition of metallic films from a liquid medium and have been shown to be a simple and cost effective way of micro-patterning [11-13]. A laser beam with a proper wavelength will travel through the liquid medium and locally generate a plasma at the liquid/solid interface. The generated plasma can dissociate the liquid at an atomic level, generating precursors at the substrate surface [14-15]. By changing the liquid components, the gaseous precursors in the plasma can be controlled. Furthermore, since the apparatus used in reactive laser deposition is simpler than that for conventional chemical vapor deposition (CVD) systems, reactive laser deposition in a liquid medium is attractive for various coating applications [16-17].

When fabricating substrates for electronic packaging applications, it is desirable to have a direct method for depositing conductor lines on a substrate material such as diamond. Various electrical conductor materials, such as gold ($4.26 \times 10^5$ /Ω.cm), copper ($5.98 \times 10^5$ /Ω.cm) and aluminum ($3.77 \times 10^5$ /Ω.cm) are used currently. In particular, gold does not readily oxidize or migrate.

In this report, we show the effect of a liquid medium on drilling of CVD diamond substrates in various liquid solutions that enhance material removal efficiency and prevent substrate cracking during drilling. Furthermore, the direct gold line writing on the diamond substrate in gold liquid medium is also demonstrated.

## 4.B Summary of the most Important Results:

### I. Experimental Method:

Free-standing CVD diamond substrates (Norton Diamond Films, Northboro, MA. USA) with thicknesses ranging from 470 to 520 μm and a thermal conductivity of about 12 W/cm K were used in this research.

A pulsed Nd-YAG laser (Continuum, PL8000/TS60) was used for drilling the CVD diamond substrates. The laser system is capable of producing 532 nm and 1064 nm wavelength beams in the visible and NIR regions respectively at a repetition rate of 10 Hz. The beam size was reduced to 6 mm using an aperture. After reducing the beam size, the beam power was

measured with a laser energy meter (OPHIR 30A-P-S, AN-2) and varied from 1 to 3 W. The beam was focused with an optical lens (Melles Griot, focal length; 100 mm). The spot size was 160 μm in air. The location of the CVD diamond substrate surface was varied between ±10 mm with respect to the location of the laser focus.

O, H, $O_2$, OH radicals are known to interact actively with carbon phases, such as graphite, diamond-like carbon, and diamond. It has been shown that the same interaction at the solid/water interlayer is possible when an oxygen rich reactive environment is generated [15]. To check the effect of various liquid media on laser drilling of CVD diamond, solutions of hydrogen peroxide ($H_2O_2$), DI water ($H_2O$), $H_2O$ + 10% potassium nitrate ($KNO_3$) and $H_2O$ + 10% potassium hydroxide (KOH) were used. $H_2O_2$ and $KNO_3$ have higher oxygen content than $H_2O$. KOH is known to produce OH radicals.

Laser light in the visible region traveling through a liquid, depending on the liquid optical properties, is partly absorbed and dispersed before impacting on the substrate surface. The energy lost due to absorption and dispersion is important when examining the economics of laser processing in a liquid medium. Table 1 lists the Nd-YAG laser beam energy loss as a function of liquid medium. The chamber used in this study had a quartz window (3 mm thick) through which the laser beam was introduced. This window caused a 14 % beam energy loss for the 532 nm beam. The beam energy was reduced by 6 % for water, 38 % for the water + 10 % $KNO_3$ mixture, 37 % for the water + 10 % KOH mixture, and 51 % for the $H_2O_2$ solution (the beam path was 100 mm in liquid medium). For the 1064 nm, the energy loss was more severe. The KOH and $KNO_3$-water mixtures completely inhibited transmission of the laser beam. Many bubbles formed in the $H_2O_2$ solution during laser processing; the main reason for the bubble

Table 1. The energy loss of laser beam depending upon the material medium.

| | Thickness | 532 nm | 1064 nm |
|---|---|---|---|
| Quartz | 3 mm | 14 % | 17 % |
| Water | 100 mm | 6 % | 11 % |
| Water +KOH | 100 mm | 37 % | 54 % |
| Water + $KNO_3$ | 100 mm | 38 % | 54 % |
| $H_2O_2$ | 100 mm | 51 % | 69 % |

formation is the high energy loss to the solution. In conclusion, for the same power level, the beam energy at the substrate surface is a function of the liquid medium composition.

The drilled holes were inspected using a scanning electron microscope (Hitachi, S-2300). The size and roundness of the holes, and the hole size difference between the top and bottom substrate surface were compared to establish the quality of the process in the different environments.

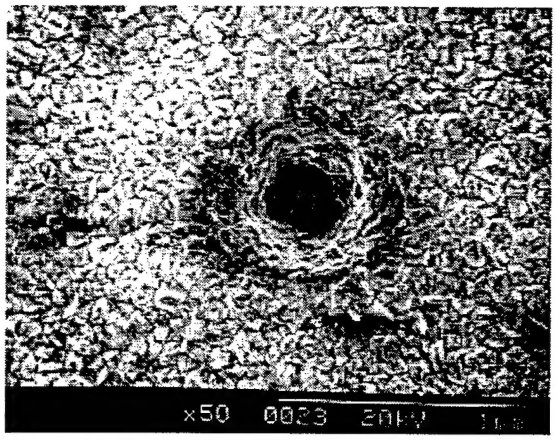
For the patterning of CVD diamond in liquid medium, a 0.1 mole solution of gold chloride ($AuCl_2$) and de-ionized water ($H_2O$) was used as the liquid medium. A pulsed Nd-YAG laser (Continuum, PL8000/TS60) and continuous wave Ar ion laser (Coherent, Innova 70) with $TEM_{00}$ mode were used for the reactive laser deposition process. The Nd-YAG beam had a Gaussian distribution. At this point, it is not known that the pulsed energy distribution changes as the laser travels in the liquid medium. While metallization, the Nd-YAG laser beam was not highly focused since the substrates could break or could be etched if a focused beam was used. The Ar ion laser beam was focused by an optical lens (Melles Griot, 01LAO059). The positioning of the substrate surface with respect to the focusing lens of known focal length was performed using a micro-positioner. The focused laser beam diameter was less than 40 μm, and the location of the substrate surface was varied from the focal point to +0.6 mm away from the focal point. During experimentation, the scanning speed (2, 4, 6 μm/sec) and laser energy density (240, 320, 400 $W/mm^2$) were varied to examine their effects on the deposition process. The substrates were immersed in the gold precursor liquid medium and the distance from the top surface of the substrate to the surface of liquid medium was maintained at about 1 mm.

The surface morphology and chemical composition of the deposited gold was examined using scanning electron microscopy (SEM) and energy dispersive x-ray analysis (EDS) (Hitachi, S-2300) techniques respectively. The surface profile of the gold deposit on the substrate was measured with a contact profilometer (DEKTAK, 3030). The electrical conductivity was measured with a four-point probe (Magnetron, M-800). The adhesion of the gold was evaluated using a cellophane tape technique (ASTM D3359-97 test).

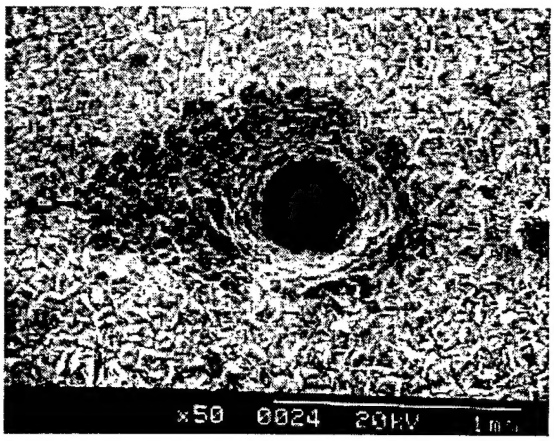
## II. Results and Discussion

### II.a Laser Drilling in Liquid Medium

Figure 1 (a) shows the top surface of a CVD diamond substrate after drilling in air with a 532 nm wavelength beam of Nd-YAG laser. Significant noise and a shock wave were generated during drilling. CVD diamond is a very brittle material; if the diamond substrate thickness is less than about 400 μm, the substrate is shattered by the laser-induced shock wave during the drilling process. As seen in the figure, the hole shape is not uniform and a heat affected zone (HAZ) can be seen on the top surface around the hole. Some cracks were observed on the bottom surface of the substrate; however, no cracks are evident on the top surface. Figure 1 (b) shows the top surface of a CVD diamond substrate after drilling in water environment with a 532 nm beam. Noise during laser processing was significantly decreased. Also, the substrate was not shattered by the laser-induced shock wave at thicknesses less than 400 μm. No cracking was observed for any thicknesses of diamond substrates. The observed HAZ was larger when processed in water than the one observed in air processing.




(a)




(b)

Figure 1. SEM micrographs of the laser drilled holes at laser entry in (a) air and (b) water environments on a CVD diamond substrate.

Figures 2(a) and 2(b) show the laser drilling time required as a function of laser power for various liquid environments using a 532 nm and 1064 nm beam, respectively. As the beam energy is decreased, the drilling time increases almost exponentially regardless of the environment and beam wavelength. Drilling time in a water environment using a focused 532 nm beam and 150 W/mm$^2$ energy density is 55 seconds. For the same conditions, it took 70 seconds

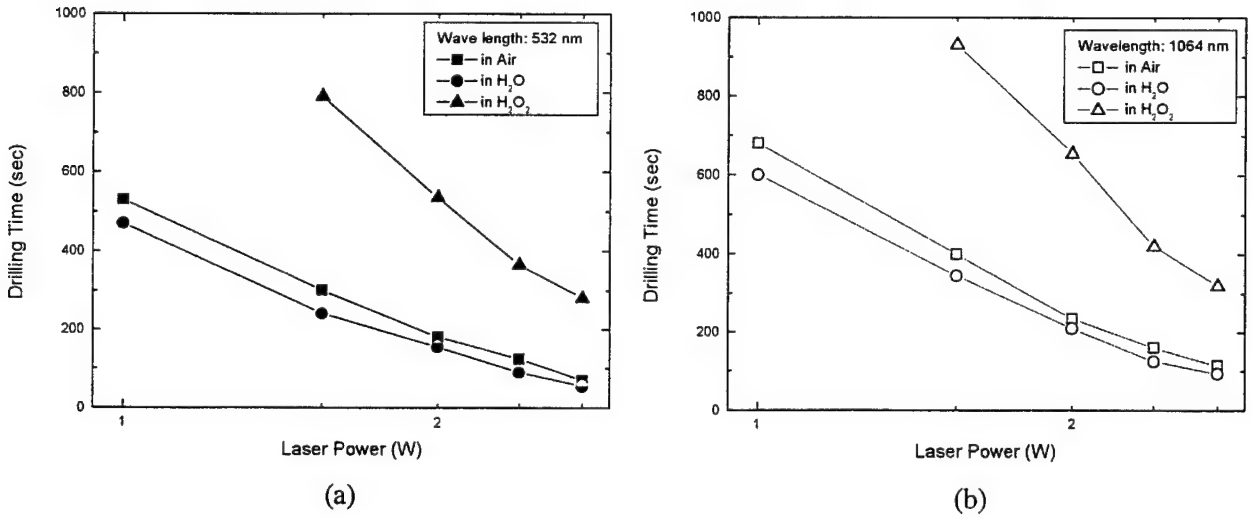



Figure 2. The plots of drilling time as a function of the processing environments and the laser powers. (a) 532 nm wavelength laser beam and (b) 1064 nm wavelength laser beam.

in air ambient. Drilling in water took less time than in air with a focused beam regardless of the beam energy density.

The laser beam chemically decomposes water molecules into active OH, oxygen(O), and hydrogen(H). The chemical bond strength of an oxygen atom to a hydrogen atom is 427.6 kJ/mol and 498 kJ/mol for $H^+$ and $OH^-$ radicals [18]. Thus, 925.6 kJ/mol is required to make an active oxygen atom from one water molecule. In air, active oxygen atoms come from oxygen molecules. There are few hydrogen molecules in air ($5x10^{-5}$ %); thus, most of the generated radicals are oxygen. The chemical bond strength between two oxygen atoms is 498.36 kJ/mol [18]. The energy required to generate active oxygen radicals in air is lower than in water; however, the oxygen content in air is only 21 %, and the air density is less than the water. This means that more active oxygen atoms can be generated in water than in air during laser processing. The $H_2O_2$ environment has even more oxygen atoms available than water; therefore, it is expected that the laser drilling time should be less. In this case, however, the drilling time is found to be longer than air or water case. $H_2O_2$ is very unstable at room temperature and oxygen bubbles can readily be seen on the liquid surface and at the liquid-container interface. The bubbles disperse the laser beam and inhibit the drilling process.

Figure 3 shows the drilling time as a function of beam focal point for the 532 nm and 1064 nm wavelength beam in water and air environments respectively. Drilling time is a function

of beam focal point location with respect to the substrate surface. As the beam is de-focused, drilling time increases from 55 to 270 second in water. For the same de-focusing distance, drilling time with the substrate located before the focal point is shorter than the substrate located after the focal point.

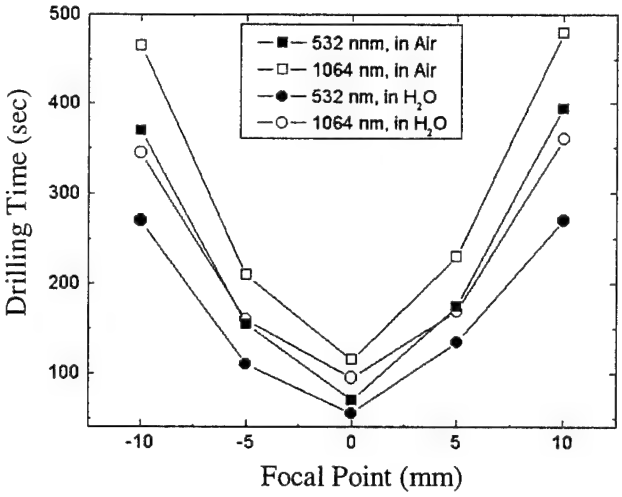



Figure 3. The drilling time depending upon the beam focal point and beam wavelength in the water environment.

When the substrate is located before the beam focal point, the laser beam rays are converging. However, when the substrate is located after the beam focal point, laser beam rays are diverging. Furthermore, as seen in table 1, the loss of the laser energy increases with the increasing beam travel distance, and, at the focal point, plasma, caused by the break down of the medium, is generated by the focused laser beam. This can contribute significantly to the energy loss. Therefore, the substrate located before focal point can receive more laser energy than when it is placed after the focal point. Consequently, drilling at the position before the focal point is faster than at a position after the focal point.

Drilling time for the 532 nm wavelength beam in water was 55 second, while the 1064 nm wavelength beam required 95 second for the same conditions. Processing with a 1064 nm beam always required more time than processing with a 532 nm beam regardless of environment and focal point. Generally, a material will absorb more of the shorter wavelength beam energy than the longer wavelength beam energy. Thus, the surface temperature of a

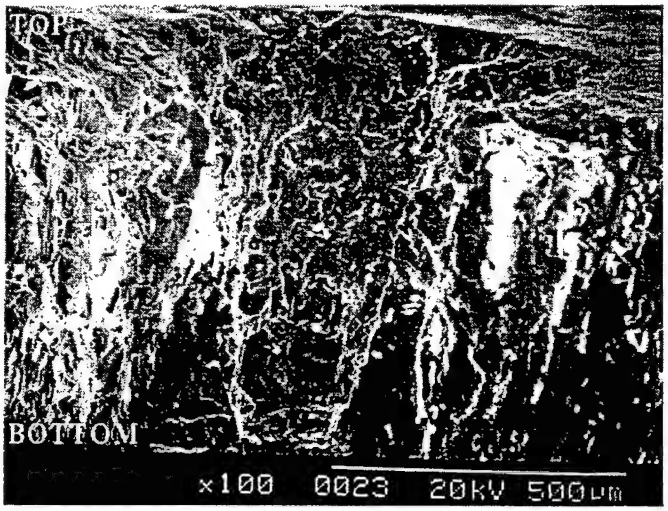



Figure 4. The SEM micrograph of cross section of a laser drilled hole on a CVD diamond substrate in the water environment.

diamond substrate illuminated by a 532 nm wave length beam will be higher than the 1064 nm wavelength beam illuminated surface. Molecules will also absorb more of the 532 nm wavelength beam energy; therefore, the 532 nm beam will generate more active radicals than the 1064 nm beam.

Figure 4 shows the typical hole cross section drilled in water environment. The wall of the hole is tapered and uneven. The hole size on the top surface is larger than on the bottom surface, and due to the plasma effect, the top surface shows a larger HAZ. The plasma effect on the bottom surface is minimal; thus, the HAZ on the bottom surface is small compared to the top surface.

Table 2. The laser drilled hole dimensions in CVD diamond substrates, as a function of the processing environment, using 532nm Nd-YAG laser.

| Environment ⇨ | | Air | $H_2O$ | $H_2O_2$ |
|---|---|---|---|---|
| | | Hole Size (μm) | | |
| Top Dimension | Maximum | 600 | 580 | 810 |
| | Minimum | 500 | 560 | 930 |
| | Average | 550 | 570 | 870 |
| Bottom Dimension | Maximum | 300 | 350 | 680 |
| | Minimum | 260 | 330 | 520 |
| | Average | 280 | 340 | 600 |

Table 2 lists hole dimensions as a function of drilling environment. The hole size in an air environment is smaller than in water or $H_2O_2$ environment. From this table, the etch rate of CVD diamond is calculated by dividing the hole volume by the drilling time. For a laser energy density of 150 W/mm$^2$ and a 532 nm wavelength, the etch rate is about 0.7 x $10^{-4}$ mm$^3$/sec in air and 20.0 x $10^{-4}$ mm$^3$/sec in water. Though the actual laser power at the substrate surface is less than in air, the diamond etch rate in water is about 28 times faster than that in air ambient. As has been described earlier, there are active radicals generated by the laser in the water environment. These active radicals easily react with the carbon atoms in the CVD diamond substrate, making $CO_x$ and $CH_x$ gas; therefore increasing the etch rate of the substrate. However, it is not clear which radical ($H^+$ or $O^-$) dominates the etching process.

Hole roundness and degree of taper are important in the manufacturing of vias in CVD diamond substrates. The hole roundness is given by the ratio of the largest hole diameter to the smallest hole diameter on the same hole. A ratio of 1 means the hole is perfectly round. The degree of the hole taper is given by the ratio of the average hole size at the top surface to that at the bottom surface. Here a ratio of 1 means that the top hole size is exactly the same as the bottom one (i.e. no taper).

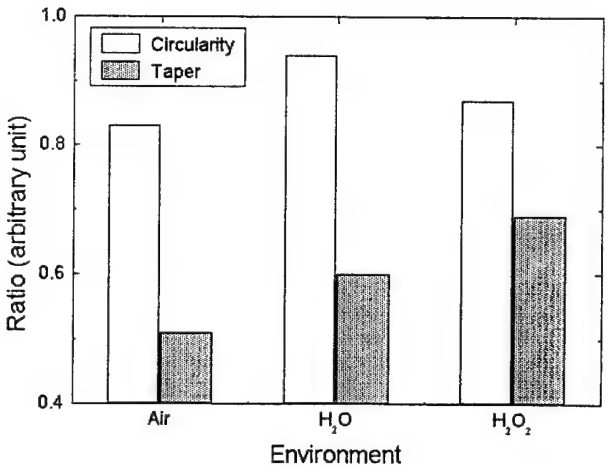



Figure 5. The laser drilled hole shape ratio depending upon the environments.

Figure 5 shows the roundness and taper for various drilling environments. Using a focused 532 nm beam and 50 w/mm$^2$ energy density, the average hole size is found to be smaller for air than all the other environments. However, roundness and taper ratios, which would define the qualities of drilled hole, are smaller in case of air (0.83 roundness, 0.51 taper) than either for water (0.94 roundness, 0.6 taper) or $H_2O_2$ environments (0.87 roundness, 0.69 taper).

Under high pressure and high temperature, diamond is known to react with KOH or $KNO_3$ resulting in gaseous by-products like CO or $CO_2$ [19]. These standard chemicals were used for polishing CVD diamond substrates (CAMPP polishing) [19]. It was expected that addition of KOH or $KNO_3$ chemicals in water would decrease the laser drilling time further, due to the increased O and OH radical concentrations as compared to pure water. However, drilling time in the [$H_2O$ + 10 % KOH] and [$H_2O$ + 10 % $HNO_3$] solutions did not decrease, as expected, when compared with drilling times in air or water environments. Drilling in the $H_2O$ + 10% KOH solution took more than 1200 seconds with a focused beam. This processing time is longer, by a factor of about 10, than the one in plain water environment. The KOH chemical completely inhibits the laser beam assisted drilling process. KOH when dissolved in water decomposes into $K^+$ and $OH^-$ radicals. We suspect that the $K^+$ and $OH^-$ radicals do not aid the laser drilling of diamond substrates. Drilling in $H_2O$ + 10% $KNO_3$ solution takes about 75 seconds, using a

focused laser beam. This drilling time was longer than that for drilling in water ambient and comparable to that in air. Thus, addition of $KNO_3$ was not beneficial to the drilling process.

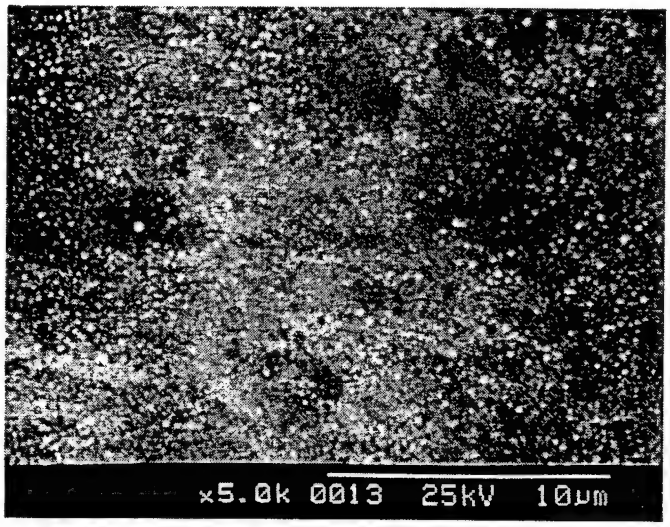



Figure 6. SEM micrograph of morphology of gold deposits on diamond substrate using an Nd-YAG laser.

## II.b Laser Patterning in Liquid Medium

To use free standing diamond as a thermal spreader substrate for electronic packaging, the patterning of circuit on the surface after its shaping, is necessary. Figure 6 is a SEM micrograph showing the morphology of the gold deposits on a diamond substrate surface using the Nd-YAG laser (532 nm beam wavelength). The diamond surface, immersed in the gold-rich solution, was illuminated by the Nd-YAG laser with 2.23 $W/cm^2$ for approximately 10 minutes. When a laser beam interacts with a material, due to high energy densities, it generates a plasma [14-15]. This plasma, generated at the liquid-material interface, can activate gold radicals in the liquid media and create active gold atoms. The active gold atoms then can deposit on the substrate surface with the aid of the heat energy produced by the laser beam and plasma. As seen from Fig. 6, nano-size gold particles (particle size less than 0.05 µm) were deposited on the diamond surface, but the gold deposit is discontinuous. Processing parameters like illumination time and laser energy density were found to have no effect on the gold particle size and density. The measured electrical resistivity of the gold deposit in this case was similar to that of a bare CVD diamond substrate, indicating discontinuities in the gold deposits.

The pulsed output of the Nd-YAG laser also ablates the substrate surface. One pulse will deposit some gold on the substrate. However, subsequent pulses tend to sputter off some of the previously deposited gold. Hence, after multiple pulses with the pulsed Nd-YAG laser, the gold deposit is found to be very fine and discontinuous. Thus, the Nd-YAG laser was found to be unsuitable for reactive laser deposition.

An Ar ion laser is a continuous wave laser that does not produce a shockwave like a Nd-YAG laser. Figure 7 shows a SEM micrograph of the gold deposit morphology on a diamond substrate surfaces using the Ar ion laser. Deposition was accomplished at 320 W/mm$^2$ energy density, 2 μm/sec scanning speed, and with the substrate surface located at the focal point.

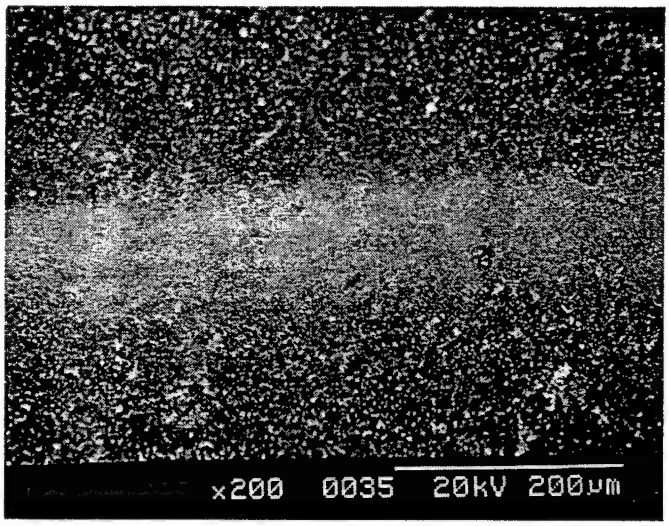



Figure 7. SEM micrograph of morphology of gold deposits on diamond substrate using an argon ion laser.

The focused spot size of the laser beam was less than 40 μm in air. However, the observed width of the gold deposit was found to be wider than the air measured spot size and varied depending on the substrate material. This is possible because the laser beam is scattered by the liquid medium, causing the laser spot to diffuse, making it larger than that in air ambient. This, in turn, leads to a broadening of the spot size and causes the edge of the gold deposit to be blurred rather than sharp. To minimize this effect, the distance from the substrate surface to the liquid surface was set to 1 mm. If this distance is reduced to less than 1 mm, the gold rich solution is not replenished sufficiently.

When the laser beam is de-focused (the laser beam mode is $TEM_{00}$), the gold deposit shows a bimodal distribution profile instead of a single Gaussian-like profile. Figure 8 shows the variation in thickness of deposited gold on a diamond substrate as a function of focal point location, as measured by contact profilometry. Gold deposition was accomplished using an Ar-ion laser at 320 W/mm$^2$ energy density and 2 μm/sec scanning speed, with the beam focused, at 0.2 mm de-focusing, and at 0.4 mm de-focusing. The gold line profiles are shown in Figs. 8(a), 8(b), and 8(c), respectively. At the focal point, the cross-section of the gold deposit line has a Gaussian profile. However, as the laser beam was de-focused to 0.2 mm, the gold deposit assumed a bimodal shape (Fig. 8(b)). The bimodal shape disappeared as the laser beam was further de-focused, and only a thin layer of gold was deposited. We assume that this phenomenon occurs for the following reason: during the reactive laser deposition process, gold

radicals must be supplied to the central region of the focused beam to generate active gold species, and activated gold species move randomly to find a suitable place to lose their excited energy [20]. This process is dominated by diffusion. When the substrate is located on the focal point of the beam, it is easy to supply gold radicals to the reaction region, the diffusion distance between the reaction region and substrate is short, and the substrate temperature is higher than that of the de-focused case. Therefore, the deposited gold has a Gaussian shape and a fast deposition rate. Once the laser beam is de-focused, the radius of the reaction region that can generate a plasma increases, and the possibility that the gold radicals can reach the center of the reaction region decreases. Therefore, the center of the reaction region becomes depleted of gold radicals compared to the focused case, where the beam size is smaller. The result is a bimodal shape. As the beam is further de-focused, the distance from the reaction region to the substrate surface increases, and the substrate temperature decreases further. This means an increase in the diffusion length for the activated gold species, which leads to a reduced deposition rate. The bimodal distribution shape then disappears. Chen et al. [17] noted that the deposit shape changes, depending on the scanning speed. However, laser beam size is the only parameter that affects the deposit shape.

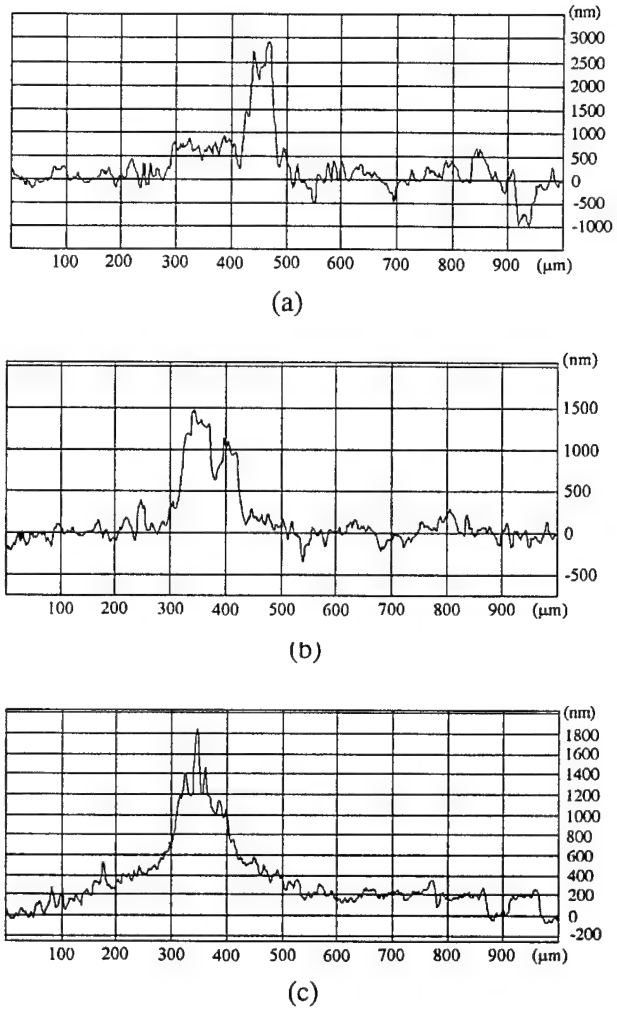



Figure 8. Contact surface profilometer plots of gold deposits on a diamond substrate as a function of location of laser focal point with respect to substrate surface at 400 mW laser power, 2 μm/sec scanning speed (a) the focal point, (b) 0.2 mm de-focused, and (c) 0.4 mm de-focused.

The chemical composition of the gold deposit was confirmed by EDS. Figure 9 shows the EDS spectrum of a gold deposit on silicon. The spectrum exhibits a strong gold signature with a weak silicon peak. The figure indicates that gold was successfully deposited onto the silicon substrate surface by the reactive laser deposition. The absence of other peaks indicates the absence of contamination. The presence of the weak silicon signal indicates that the gold deposit is not uniform or dense.

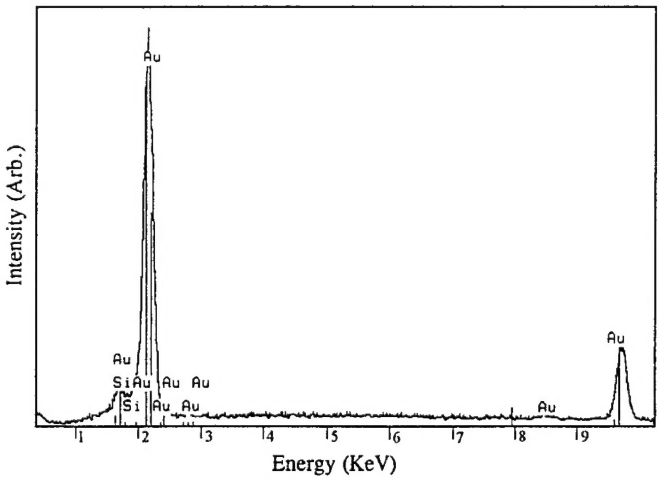



Figure 9. EDS spectrum of gold deposits on a silicon substrate.

Figures 10 show SEM micrographs of the gold morphology on a diamond substrate, deposited at 320 W/mm$^2$ energy density, 2 μm/sec scanning speed, and with the substrate surface at the laser focal point. The deposits show an aggregation of gold particles of circular shape. The average size of gold particles on the silicon, alumina, and diamond substrates are 0.1 μm, 0.1 μm, and 0.08 μm, respectively. The gold particle size depends on the scanning speed, the laser power, and the beam focusing. By increasing the scanning speed, decreasing the laser power, and de-focusing the beam, the particle size and deposit density are reduced.

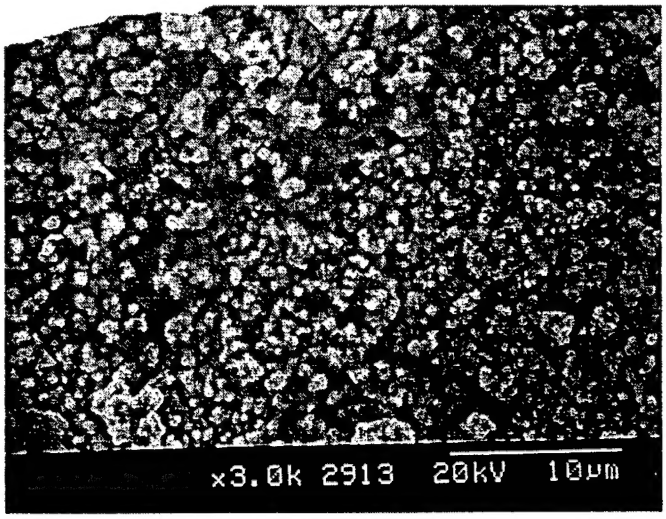



Figure 10. SEM micrograph of morphology of gold deposits on diamond substrate.

The electrical sheet resistance of the gold deposition (carried out at 320 W/mm$^2$ energy density, 2 μm/sec scanning speed, and with the substrate surface at the focal point) was measured to be about 0.3 Ω/□ (electrical resistivity, $\rho=3\times10^{-7}$ Ω-m) using four-point probe,

regardless of the substrate properties. This value is similar to that of a 5 μm thick gold film deposited by electroplating.

The adhesion of the gold to the substrate was not sufficient to allow its use as a conductor line in semiconductor technologies, such as packaging, multi chip modules, etc, because the gold deposit could be pealed off using cellophane tape. Gold is a noble metal and diamond is chemically inert. Hence, there is no chemical reaction between diamond and gold, and the adhesion between them is poor. However, we believe the adhesion could be improved by using precursor liquid for Ti, Cr etc. with laser processing, prior to pure gold coating.

**III. Conclusions:**

Results of this study show that the drilling of a CVD diamond in a water environment is about 28 times faster than in air. Better hole quality as well as a reduced noise and no substrate shattering were observed in the water environment; however, hole size for the water environment case was larger than in the air case under the same processing conditions.

KOH, $KNO_3$ and $H_2O_2$ solutions did not have any beneficial effects in the drilling of diamond substrates. Bubble generation and enhanced optical absorption of laser beam were the primary factors preventing the KOH, $KNO_3$ and $H_2O_2$ solutions from having any positive effects on the drilling process.

After the shaping of the diamond substrate in the liquid medium, gold was successfully deposited on diamond substrates using an Ar ion laser by simply changing the liquid medium. The gold deposit exhibited higher (about 15 times) electrical resistivity than that of pure bulk gold. The gold deposition rate in a reactive laser deposition process was found to decrease with decreasing laser energy density, increasing scanning speed, and de-focusing of the laser beam. However, the width of the gold deposit was only a function of the beam focal point. The adhesion of gold to the diamond substrates was poor. Therefore, further investigation of reactive laser deposition as a function of deposition parameters in an effort to improve adhesion is recommended.

## 4.C List of all Publications and Patents:

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1. B. S. Park, A. P. Malshe, A. Muyshondt, and W. D. Brown, 'The Effects of Substrate Properties on Metal Coating from Liquid Medium by Reactive Laser Deposition', Surface and Coatings Technology, (accepted)

2. B. S. Park, A. P. Malshe, A. Muyshondt, and W. D. Brown, 'Pulsed Nd-YAG laser induced Reactive Drilling of Diamond Substrates', (under preparation)

### 4.D. List of Participating Scientific Personnel:

Researchers other than PIs,

Dr. W. D. Brown

Dr. A. Muyshondt

Dr. Park (Post-doctoral Fellow)

Mr. Jamil (MS student)

## 5. Report of Invention:

- None-

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